Methods for Folding Linkages Out of Carbon Fiber

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Abstract. This paper presents a fabrication technique used to embed folds into carbon fiber composite sheets through controlled discontinuities between elastic silicone and rigid epoxy, so that it may be possible to construct moving linkages out of a single starting layup. Fold lines are designated with a photosensitive silicone adhesive, cured with UV light, and epoxy is cured into carbon fiber sheets under vacuum bagging. The containment of 'leaks' between the silicone and the epoxy was one of the main challenges in the implementation of this technique. Two methods of fabricating carbon fiber flexures were explored: stiffness through geometry, and stiffness through materials. The former uses origami concepts to produce geometric structures resistant to bending and compression. While the method showed promising results on paper prototypes, its complexity caused many issues when implemented on carbon fiber. The method of stiffness through materials uses controlled changes in the number of carbon fiber plies used in the layup (4 on fold lines, 8 everywhere else) to provide additional stiffness, leading to less complexity. The methods of this paper can be used to fabricate lightweight, stiff, monolithic linkages, with links that can sit flush to a surface, then fold out of them. Applications include movable aerodynamic structures with utility in the automobile and aerospace industries.

Keywords: Mechanism prototyping · Composite flexures · Linkages

1 Introduction

The component-level design of linkages often leads to cumbersome assemblies that occupy a lot of space with heavy bearings, large material allotments to hold those bearings, backlash issues, and a large number of components. Component-level design takes place after type synthesis and dimensional synthesis are complete. This works aims to the reduce component-level weight and complexity of linkage mechanisms connected with revolute joints by fabricating them as fold lines out of lightweight composites. In the world of figurative origami, many designs use the ability of folds to act as joints to produce desired motions between sections of the same piece of paper. For example, consider the classical origami

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design of a bird that flaps its wings when its tail is pulled [16]. Since the first mathematical implementation of dynamic origami, in the form of the Miura-Ori [21], there have been many projects that have attempted to recreate such structures for engineering purposes. The primary medium of origami is paper, which has structural properties that make it suitable for only a select number of applications. As a result, many research groups have attempted to incorporate folding into existing manufacturing techniques. Work carried by Zhao et al. [31] produced a design paradigm able to implement folds into materials 3D-printed using light-processing techniques, which led to the fabrication of soft robots and metamaterials. A study by Islam et al. [11] developed a method to rigidify cellulosic paper through carbonization. While these design techniques effectively produce folding mechanisms, due to the limited range of materials they use, their applications are somewhat restricted to relatively small scales or forces. Because of this, at higher scales, composites and metal have been generally preferred by researchers. Using methods that directly affect the properties of materials to produce folds, other studies implement techniques that layer cutouts made out of rigid materials on flexible sheets, thus creating controlled discontinuities that allow for the implementation of folds. For such techniques, carbon fiber has been the preferred material due to its strength-to-weight ratio, as shown by prototypes developed by Sakovsky and Pellegrino [25], Al-Mansoori et al. [1], and Deleo et al. [6]. The compliant properties of carbon fiber, and the composite's behavior and internal stresses during folding motion was tested and modelled in a study by Fernandez and Murphey [8]. In addition to these projects, Reynolds et al. [22] combined one of the techniques developed by Pellegrino et al. [26] with 'traditional' bending analysis to design a deployable RF reflector for spacecrafts. Promising results have also been obtained from other materials as well. Examples of this include the work conducted by Zhu et al. [32] which led to the implementation of origami folds in fiberglass-reinforced shape memory epoxy, and a study by Wang et al. [27], in which folds were embedded in aluminum through the use of controlled cuts.

The embedding of folds in otherwise rigid material has lead to several interesting engineering artifacts. The Tachi-Miura pattern [30], created using cured composite cutouts sandwiched around flexible urethane, allowed for the production of deployable structures able to effectively distribute high loads through controlled deformation, as shown by a study by Deleo et al. [7]. Lee et al. [18] folded the water-bomb tessellation out of paper and kapton to create a deformable wheel that changes shape for different terrains. Due to its thermal properties, kapton was also found to be an effective medium for origami applications in the aerospace industry, as shown in concepts by Wilson and Pellegrino [29]. The ability to precisely embed folds on a composite made out of posterboard and polymer films [9,28] has enabled millimeter-scale robots inspired by insects, such as cockroaches [3] and flies [20]. The versatility and creative range provided by the usefulness of origami in many engineering applications motivates our work. Here we present a way to embed flexible folds in otherwise rigid carbon fiber. Prior work by Pellegrino and others [19,24,25] was used as reference for the development of specific process parameters. In addition to this, the work of Cozmei et al. [5] exhibited similar manufacturing methods and prototyping goals. A study by Chillara and Dapino [4], in which active aerodynamic parts are obtained from morphing laminated composites, although not directly related in terms of techniques, is still relevant in terms of prototyping goals. In this work, we hope to delineate general methods for folding a wide variety of linkages out of carbon fiber, providing the ability to produce one-piece linkages in a streamlined fashion. The method of stiffness through geometry uses interconnected origami structures explicitly designed to provide rigidity within a given link. The method of stiffness through materials uses changes in the number of plies in carbon fiber composite to compactly provide stiffness. The novelty of these methods does not necessarily lie in the manufacturing techniques used to make parts, since similar procedures are cited above. Instead, we develop manufacturing procedures for the integration of folds into otherwise rigid material for the general fabrication of linkages.

2 Materials and Methods

Starting from raw carbon fiber and epoxy resin, a rigid composite can be obtained through three different methods, listed here in order of complexity: hand layup (no vacuum, no heat), vacuum bagging (vacuum, no heat), and oven curing (vacuum, heat) [15]. Vacuum bagging was chosen as the preferred method for prototyping origami-like folds as it is more precise than hand layups, and the layup size is not constrained by the size of an oven. Figure 1(a) shows a schematic of the vacuum bagging curing process for a flat sheet. Vacuum film and vacuum tape are used to seal the composite-to-be from the surrounding environment. Subsequent layers of release film and breather fabric are laid over the composite sheet to prevent excess epoxy from entering the vacuum pump pipe system. In Fig. 1(a), "CF Layup" indicates the stack of raw carbon fiber plies impregnated with epoxy resin to be cured into a rigid sheet. Any subsequent figure referred to as "Layup" indicates in detail the setup of the various materials to be cured using vacuum bagging. Glass is the preferred surface for carbon fiber curing

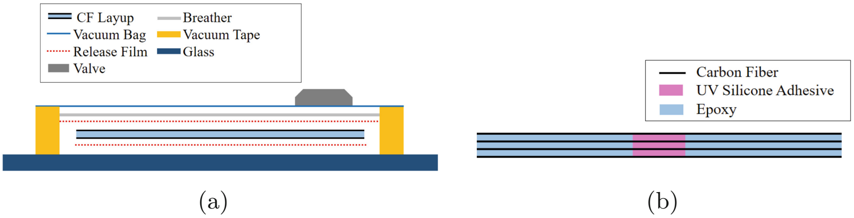


Fig. 1. (a) Schematic of a standard vacuum bagging curing process for a flat sheet of carbon fiber. Subsequent figures labelled as "Layup" indicate the layer arrangement to be vacuum bagged. (b) Layup of a single fold embedded into a four-ply rigid sheet of carbon fiber. Epoxy produces rigid sections, silicone produces flexible, elastic sections in the form of folds.

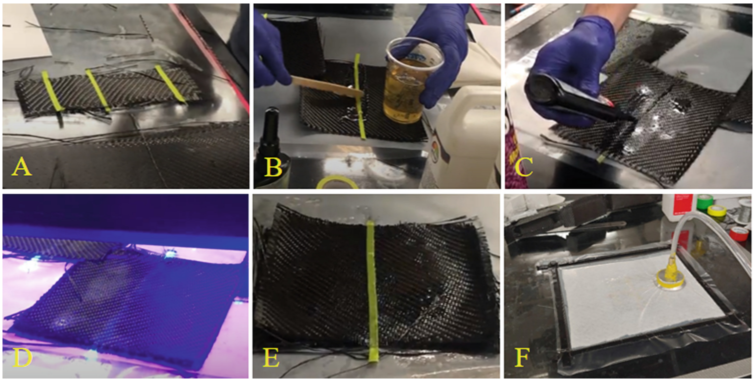


Fig. 2. Step-by-step sequence for the layup of a fold embedded into a four-ply carbon fiber sheet. (A) The application of a fluorescent tape mask over desired fold lines. (B) The addition of epoxy resin around masks. (C) The insertion of UV silicone adhesive in the masked area. (D) The formation of two two-ply sheets and subsequent UV irradiation to cure silicone (only one shown). (E) Stacking and alignment of two two-ply sheets to form a final four-ply layup. (F) Vacuum bagging for at least 10 hours to cure epoxy.

because of its smoothness and for cleaning purposes. To prevent the layup from sticking to the glass after curing, a release film was used.

Starting from the standard vacuum bagging procedure, surfaces able to fold relative to each other were produced by implementing discontinuities in the epoxy matrix in the form of lines made out of silicone, which was selected for its elasticity, and due to the fact that it does not mix with epoxy, thus producing sharp margins. Figure 1(b) shows the cross section of the layup used to produce a single fold between four plies of carbon fiber reinforcement. The parts that are impregnated with epoxy come out rigid, while the parts that are impregnated with silicone remain flexible and can fold.

It is a challenge to produce sharp and precise discontinuities between rigid and flexible areas. If multiple different resins are inserted into the reinforcement, putting the layup under vacuum causes resins to migrate from their desired positions. In order to prevent this from happening, a UV-activated silicone adhesive was used, and the procedure shown in Fig. 2 was implemented. To produce a part, four layers of raw carbon fiber were used. Each ply consisted of 2×2 twill weave (referring to the fact that each tow passes through two other tows to form a sheet) with a 3K tow manufactured by Composite Envisions (Part No. F-1902). To start, masks for the desired fold patterns made out of fluorescent tape were applied on two carbon fiber plies, which will become the two outer layers (Fig. 2A). Epoxy resin is then applied to each ply (Fig. 2B). For the two initial steps, only a small amount of epoxy is required (just enough to cover the area 2 to 3 cm away from each of the folds). The purpose of this initial light application of resin is solely to produce the margins between the flexible silicone and the rigid epoxy matrices. More resin is used in subsequent steps.

Fluorescent tape that is resistant to soaking resin was selected for making masks. This tape is convenient because it is visible through small openings in the twill weave carbon fiber fabric. This makes it convenient to locate the position of folds, which is advantageous for aligning and stacking plies. The application of a mask makes it so that the covered regions of the plies do not saturate with epoxy resin, leaving space for the silicone to be applied. Because of the permeability of raw carbon fiber, some of the epoxy inevitably diffuses inside the masked area. A mask width of 4 mm was experimentally determined as the optimal width to produce non-rigid regions that successfully approximate a one-dimensional fold. Thinner masks do not produce folds, and wider masks lead to flexible areas that possess non-negligible translation degrees-of-freedom. The epoxy and hardener used for prototyping in this paper were both manufactured by Composite Envisions: parts no.'s 1159 and 1161, respectively. The mix ratio was 3:1 by volume (100:32 by weight). While it is common practice in the making of carbon fiber composite to use a 1:1 weight ratio between epoxy resin mix and carbon fiber reinforcement, a 4:3 ratio is preferred for this process. This is because many steps require the parts to be flipped upside-down and moved around, and this inevitably causes the epoxy mix, which during these stages is still fluid, to drip and leak out.

After masking the plies and marking the margins with epoxy, the silicone adhesive is injected into the dry area left underneath the fluorescent tape (Fig. 2C). Each of the masked plies is then covered by an additional layer (on the side opposite to the mask) with epoxy, thus forming two two-ply sheets (only one is shown in the figure). Ultrabond 721 UV silicone adhesive by Hernon was chosen as the preferred elastic matrix because of its ability to re-emit a purple color when irradiated with UV, making alignment and stacking simpler. In order to join the two pairs of sheets, depending on how much epoxy was initially used to cover the areas around folds, 60% to 70% of the epoxy resin mix is used. The two resulting two-ply sheets are then irradiated with UV to cure the silicone (Fig. 2D), thus preventing fold lines from changing shape. Depending on the amount of silicone injected into the fiber, the fluorescent tape masks may have to be removed to allow for another irradiation on the opposite face of the sheets. Finally, the two sheets are stacked on top of each other forming the final layup (Fig. 2E). For this step, the masks can be used to align the two parts and to ensure that the fold areas are on top of each other. If the tape is for some reason removed, the fluorescence of the silicone under UV can also be used as a visual cue for alignment. When joining the pair of two-ply sheets, the remaining epoxy is used. The layup is cured for at least 10 h within a vacuum bag at a negative pressure of around 0.9 Bar at room temperature (Fig. 2F). Curing temperatures for a given layup depend on the type of plies used as composite reinforcement, but higher temperatures have positive effects on the density of the resulting composite, its shear strength, void content, as well as the degree of curing of epoxy, as shown by Koushyar et al. [14]. As shown by Romhany and Szebenyi [23], interlaminar crack propagation could have been reduced by adding multiwalled carbon fiber nanotubes in the epoxy mix during the layup procedure. It should be noted that the samples produced in this paper were not validated according to ASTM protocol for strength and fatigue.

2.1 Folding Carbon Fiber to Form Stiff Links - Stiffness Through Geometry

While this layup procedure allows for precise folds to be embedded in rigid carbon fiber, this method's main limitation lies in the fact that the material properties of carbon fiber composites are directly related to the number of raw fiber plies used as reinforcement. Here we investigate how to incorporate U-beam sections and revolute joints into a fold pattern to create mechanism links with greater out-of-plane stiffness. A geometrically rigid structure would employ static folds, which are well known and commonly used in the world of figurative origami. Traditionally, there are many fold combinations, such as sink folds and reverse folds, that are known for being able to "lock" paper in a given configuration. This means that if all the creases on a given sheet were collapsed together, only one rigid (relative to the flexibility of the material being folded) configuration would be obtained [17].

One such combination, known as the rabbit ear fold, was used to produce static folds (i.e. folds that are meant to keep a sheet in a specific configuration). While the traditional rabbit ear fold, which takes advantage of 22.5° geometry, can only produce flat collapses (fully folded crease patterns), a variation that uses 45° geometry is commonly used in origami to produce three dimensional shapes. The crease pattern presented in Fig. 3(a) shows a structure that gains rigidity by producing a three dimensional configuration with the cross section of a U-beam. It is common practice in the presentation of origami designs to describe a given folded structure using a crease pattern that showcases every fold that is used to produce a given shape. This allows for the majority of the folds that make up a design to be displayed in a synthetic fashion. It is also common in crease patterns to distinguish between mountain and valley folds. This is to allow folders to clearly identify the direction of each of the creases. Valley folds indicate creases that fold like the pages of a book from the reader's point of view (a "V" shape), while mountain folds are oriented in the opposite direction (an upside-down "V"). For a crease pattern that follows this convention, there is only one way in which a sheet can be collapsed, thus making the instruction steps of complex models relatively simple (modern origami designs take several hundreds of steps, and a single crease pattern can encompass a folding procedure that can take several hours to complete). The structure presented in Fig. 3(a) uses the combination of two 45° rabbit ear folds to produce four surfaces perpendicular to each other. The name "rabbit ear" comes from the fact that this fold combination produces an outward facing flap that looks like the ear of a rabbit. If this crease pattern were to be mirrored about a horizontal axis, the fold combination for a simple box would be obtained. Because of this, the origami structure in Fig. 3(a) is called a *half-box base*. Both the paper and the carbon fiber versions of this base, as shown in Fig. 3(a), are left partially undone to make it easier to see the folds that would collapse. To evaluate the prototype's ability to produce sharp

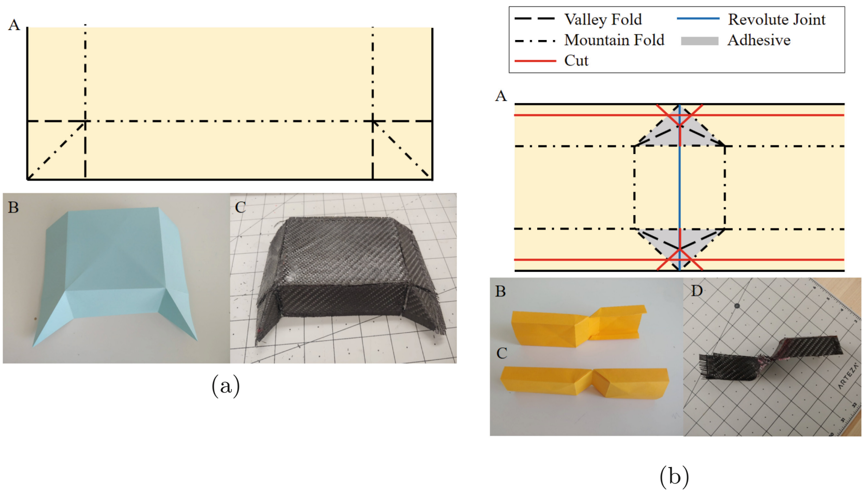


Fig. 3. (a) The crease pattern of the half-box base, and versions of it folded out of both paper and carbon fiber. The paper creases are sharp, while the carbon fiber creases are rounded. (b) The crease pattern of the mirrored double-pleat fold, and versions of it folded out of both paper and carbon fiber (four plies). Paper versions include both the specular configuration (capable of 360° rotations, marked with "B") and the flipped configuration (capable of 270° rotations, marked with "C"). The carbon fiber model exhibited less precise fold lines than paper.

folds, its quality was compared against its paper counterpart. The construction of the half-box base out of carbon fiber composite was used to refine our masking, layup, and curing procedures. Through these activities, the optimal mask width of 4 mm was determined.

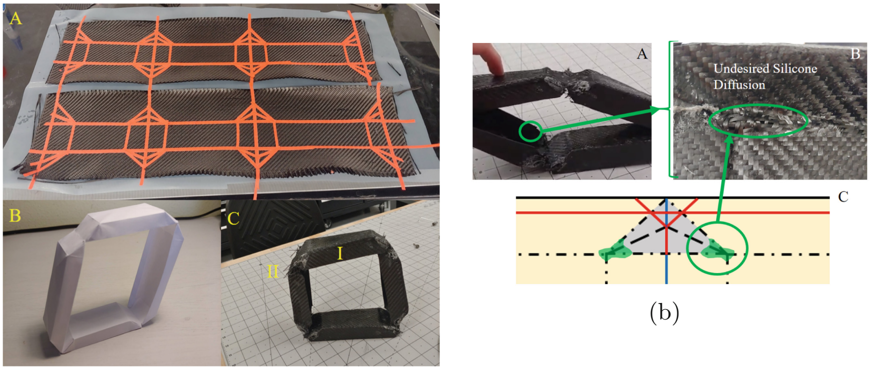
Starting from the crease pattern for the half-box base, a structure for a single revolute joint was developed by changing the angle offset of one of the edges of the box to 135°. The resulting origami structure is the mirrored double-pleat fold, which allows for the production of long U-beams. A crease pattern for this structure is presented in Fig. 3(b). This fold combination was employed as a result of experimentation on paper prototypes, balancing range of motion, time to assemble each link, and complexity of the folds. Crease patterns that produced I-beams were also devised, but due to their complexity, they were not carried forward. In its final iteration, the mirrored double-pleat fold produces links that have half the width of the starting sheet, while the length is reduced by a factor of $\frac{\sqrt{2}}{4}\tan(22.5°)$ multiplied by initial width. This geometric relationship allows to build link lengths in accordance with a kinematic design.

Depending on the direction of the folds of each side of the joint relative to each other, the bodies of each of the links can be oriented according to different packaging or range of motion requirements. If the crease pattern is followed exactly, the joints will be in the configuration presented in Fig. 3(b)B (specular configuration), while if the fold direction is inverted for one of the links (mountain folds are made into valley folds and vice versa), the joint configuration presented in Fig. 3(b)C is obtained (flipped configuration). Depending on the specific needs of a given joint, either configuration could be more advantageous. If a full 360° motion is desired, the flipped configuration can be used in such a way to allow the links to nest into each other, while the specular configuration is only capable of a range of 270°. Because of the planar constraints of origami, motion exceeding 360° cannot be obtained using this method, thus making fully rotatable connections impossible. Fold patterns that allow for single and double shear joints were developed using paper, but due to their complexity, they were not carried forward into carbon fiber models.

The mirrored double-pleat crease pattern shown in Fig. 3(b) is a simplification of a more elegant link design that does not require the use of adhesives to keep the final structure together. This design was used for the paper links, but the number of additional folds, and their size relative to the total assembly made it so that implementing this method in carbon fiber would cause scaling and layering issues due to the thickness of the medium, requiring the resulting parts to be so large that many of the approximations of folds as one-dimensional lines would not apply anymore. Because of this, it was deemed more convenient to use adhesives and additional cuts to keep the final structure rigid. During the prototyping stage for this method, Loctite 495 super glue was used to keep the links together, and the resulting layups were cut using a band saw.

Prototypes of single joints showed promising results for the mirrored double-pleat fold. Next, we tested their functionality in a four-bar linkage. Figure 4(a) shows the mask pattern for a four-bar mechanism, and its subsequent implementation with both paper and carbon fiber. By increasing the complexity of the parts, it was possible to reveal many of the limitations of crease pattern which had not become evident during the prototyping of smaller, relatively simple parts. As it can be clearly seen, the carbon fiber part is much rougher than its paper counterpart.

Firstly, for larger parts (the initial sheet for the four-bar was about 1 m in length) the movement of the plies during the layup caused regions of fiber to slide and move relatively to each other, forming wrinkles of various sizes. While this is not necessarily a problem during the resin application process, since these movements can be corrected by hand, they produce unpredictable results if they are unresolved by the time the layup is put under vacuum. If such movements of fiber are small relative to the size of the entire layup, and if they happen in one of the inner layers, they are difficult to notice. Whenever the layup is flattened by the vacuum, the wrinkles formed by movements in the inner layers cause divots susceptible to stress concentrations as the epoxy hardens. If the already-hardened silicone is strong enough to oppose these movements, pleats and discontinuities in the otherwise smooth surface of the composites are produced; if the sliding continues through the silicone, some of the folds widened, deformed, and, in some extreme cases, eliminated completely. For this reason, surfaces that should be flat, such as the one on top of the top link in the four-bar (Fig. 4(a)I),



(a) (b)

Fig. 4. (a) A four-bar mechanism using mirrored double-pleat joints showing the difference in fold quality between paper and carbon fiber. Shown are the fold mask used for the carbon fiber layup, and versions of the linkage folded out of paper and carbon fiber. The carbon fiber linkages exhibited a warped surface (marked with "I") and protruding strands (marked with "II") caused by sliding and wrinkling of layers during curing. (b) Undesired silicone adhesive diffusion in the presence of 22.5° folds. Shown is the (A) the location of diffusion on a revolute joint, (B) a close-up of diffusion on folded carbon fiber, and (C) the location of diffusion on the crease pattern.

come out curved by the end of the curing process. This curving phenomenon is caused by a combination of folds coming out misshapen and widened, causing an irregular stress distribution throughout the sheet. Secondly, misalignments in areas with many creases caused the epoxy to push into the silicone, and vice versa, preventing the composite from curing properly. Whenever the parts are cut after the vacuum bagging process, many of these uncured regions are exposed, causing the material to disassemble such that individual fibers may be pulled out. This can be seen at the top left joint of the four-bar in Fig. 4(a)II.

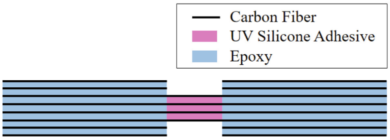
Finally, the roughness of this prototype is caused by an issue when working with 22.5 ° folds. While it is expected that the epoxy should diffuse under the mask when applied (otherwise the resulting flexible areas are too wide), this does not happen when two folds cross each other at a small angle. If this happens, whenever the silicone is injected into the fiber, it diffuses instead of being stopped by the surrounding epoxy. This ends up producing a flexible region which is larger than the desired area, as shown in Fig. 4(b). Given this phenomenon, sharp 22.5° folds are difficult to fabricate in a reliable manner, since with the current process it is not possible to observe if epoxy has penetrated under the mask until after the curing is complete. The effects of undesired silicone diffusion are shown in Fig. 4(b)B. The occurrence of this defect is common enough that it will hinder the reliable fabrication of any crease pattern that contains a large number of 22.5° folds.

2.2 Increasing Plies to Form Stiff Links - Stiffness Through Materials

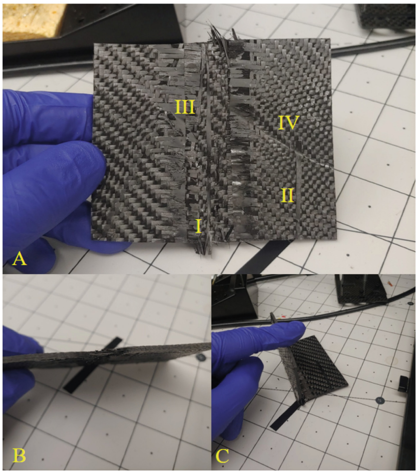
A second technique was investigated in order to overcome issues arising from the inability of the geometric implementation of the four ply layup to successfully reproduce specific fold combinations, and to reliably imprint a large number of folds. In this technique, link stiffness is achieved by increasing the number of plies instead of folding U-beams. As shown by Anto et al. [2] the number of plies used in a hybrid composite, such as carbon fiber, is directly tied to its stiffness.

Initially, it was attempted to increases the number of plies to eight, then follow steps A through F of Fig. 2. However, with the additional thickness, range of motion was lost and joints would develop cracks that eventually lead to failure. Instead, an alternate approach was developed that would only reinforce the non-flexible parts of a given layup. Starting from the four-ply procedure previously described, additional, smaller cutouts were selectively added to the regions around folds, making it so that the final product would remain thin on the areas immediately around folds, while the rest of the layup would be thicker and stiffer. Figure 5(a) shows a schematic of this approach. Most of the layup is made out of eight plies, while the folds are composed of four plies. In terms of layup procedure, this method follows the same procedure previously presented, with the additional step of adding two extra layers over and under each rigid region after the four-ply part is obtained. In order to do this, smaller cutouts are brushed with epoxy resin, and are laid over the main part aligning their margins with the outer edges of each fold line.

Figure 5(b) shows an individual joint produced using this method. As it can be seen, the interface between the fold and the surrounding rigid areas appears quite fragmented and irregular. The unweaving of fibers is caused by the handling of small cutouts while setting up the layup for curing. Particular attention should be paid during the layering of the additional reinforcement layers. Compared to the U-beam folding technique, this technique can be used to fabricate smaller scale linkages. Although parts obtained through this method generally come out sharper than by the U-beam folding method, imperfections still occur. Whenever a fully-cured layup is cut, the regions around a joint tend to produce a few protruding fibers (Fig. 5(b)I). This is because they are impregnated with silicone which, unlike epoxy, is not as effective at keeping fibers together. However, these protrusions do not hinder the functionality of the joint, and can be removed with scissors. Additionally, poor handling of the raw carbon fiber cutouts can lead to protruding strands in the rigid regions (Fig. 5(b)II), and can cause partial or full unweaving of the outer layers (Fig. 5(b)III). While the former only hinders the aesthetics of the fiber, with no appreciable effects, the latter can reduce the structural integrity of the material around the joint. Because of this, making sure that the weave in the outer layers remains intact until the layup is put under vacuum is important. Finally, if wrinkles are left on the vacuum bag whenever it is connected to the vacuum bagging tape, they will cure permanently into the part (Fig. 5(b)IV). These wrinkles are innocuous so long as they do not cross over fold lines.



(a)



(b)

Fig. 5. (a) Layup of single four-ply fold embedded into an eight-ply rigid sheet of carbon fiber. (b) A sample of an eight-layer revolute joint shown from the top view and two side views. Highlights: (I) Silicone-impregnated protruding stands caused by unweaving after cutting, (II) epoxy-impregnated protruding strand caused by mishandling before curing, (III) unweaving of outer reinforcement layers caused by mishandling before curing, and (IV) a wrinkle from vacuum bag misalignment.

Construction of joints following Fig. 5(a) was simpler than following the crease pattern of Fig. 3(b). With less folds, defects were reduced related to layer misalignment, layer migration under vacuum, and resin diffusion over small angle crease intersections. The layup of a part with five different joints could be set up in less than two hours. Furthermore, this method produces smaller links and joints, which facilitates the spatial packaging of a linkage. This method also aids in the fabrication of *branching links*. Figure 6(a) shows how this is made possible through the addition of *separation sheets*, in the form of vacuum film sandwiched by release film, that prevents plies that are part of the same layup from connecting to each other. Given the fact that multiple of these separations can be produced, one layup can produce a body which includes multiple kinematic chains. This makes the construction of complex mechanisms less dependent on the size of the initial raw fiber sheets, which was problematic when forming the layup of U-beam crease patterns. Another structure that becomes possible is a double shear joint, shown in Fig. 6(c). Because a fold necessarily needs to be between connected surfaces, the resulting part has a support piece (shown in light red) that does not belong to the kinematic chain. Double shear joints usefully eliminate or minimize out-of-plane moments that arise from reaction force couples at a revolute joint.

3 Example Prototype - Active Aerodynamics

To demonstrate the eight-ply technique, it was used to fabricate an aerodynamic control surface. It is favorable to construct such a mechanism from a high stiffness-to-weight composite. In automobile applications, active spoilers can reduce turbulence and increase fuel efficiency at various speeds [12]. Active aerodynamics can also improve handling at high speeds [10]. Wings serve the role of increasing downforce to enable greater cornering speeds, but at the cost of increasing aerodynamic drag. With active aerodynamics, wings can be deployed only when cornering or braking. In a different application, aircraft use a variety of control surfaces to stabilize flight and control their orientation [13]. Fabricating such mechanisms from lightweight, stiff composites is beneficial to flight endurance and fuel economy.

The fabricated model is envisioned as an active automobile spoiler. The layout of the carbon fiber ply configuration is shown in Fig. 6(b). The spoiler prototype, a schematic of which is presented in Fig. 7, consists of a four-bar mechanism where two of the links, the ground and the output rocker (the spoiler itself) consist of larger flat areas to direct airflow, while the other two links are used for actuation. As it can be seen in the schematic, the design uses the *branching link* connection to unite the top and bottom pairs of links. This allows for the bottom

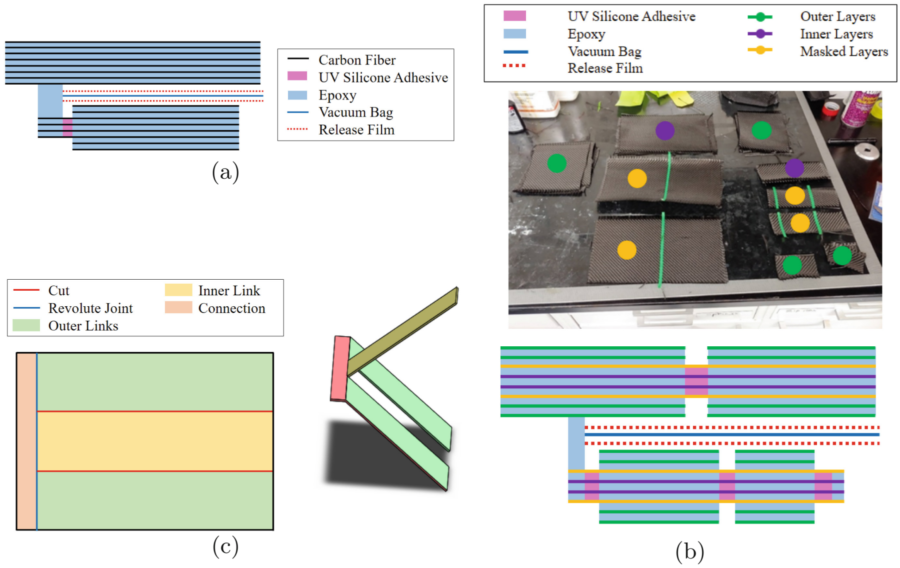


Fig. 6. (a) Layup schematic of branching joints, which enable the connection of separately cut layups. (b) Schematic of fold and cut locations needed to obtain double shear revolute joints. (c) Layup for active aerodynamic spoiler, including reference to carbon fiber cutouts used. Each of the main layers in the layup use 2 inner structure layers, 2 masked layers, and 8 outer cutouts.

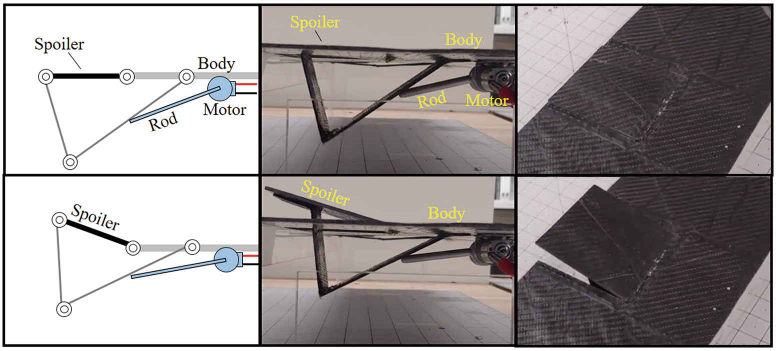


Fig. 7. Kinematic diagram of active aerodynamic spoiler, paired with pictures of the mechanism. A rod connected to a motor is used to exert a force on the mechanism. When no force is applied, the spoiler lies in the horizontal position.

links to be much smaller in width than the aerodynamic components (ground and spoiler). In theory, because of the separation between the upper and lower links, this design could be implemented independently of shape and size of the mounting surface. By extending our technique for usage with curved molds, rigid links may be formed into aerodynamic shapes. For this paper, we focus on the construction of kinematic joints.

Figure 7 shows the fabricated model of an active spoiler. When stowed, the spoiler sits flush in a large, flat surface, representing a body panel. In its deployed state, the spoiler rotates upward. The connection between the spoiler and the body is a double shear joint similar to Fig. 6(c). Figure 7 shows a view of the motion of the four-bar as the spoiler is raised. The spoiler is deployed by a motor that pushes on a rocker link with a rod. The spoiler is returned by elastic energy stored in each composite flexure. In application, the downforce acting on the spoiler can also function as a return force. The lengths of the two lower links can be determined depending on the desired range of motion for the spoiler, which is dictated by the specific application, while the length of the rod is dictated by the desired mechanical advantage, which depends on the actuator's specifications.

4 Conclusion

The objective of this project was to produce a technique to embed flexible regions that act like origami folds into otherwise rigid carbon fiber composite for the purpose of fabricating lightweight, stiff linkages. Step-by-step procedures allow for the fabrication of both static and dynamic folds to produce both stiff links and revolute joints. This objective lead to the formation of two composite layup procedures that use discontinuities between epoxy resin and UV-cured silicone adhesive to achieve foldability. The first procedure used a crease pattern to fold a kinematic chain of U-beams, while the second procedure obtained link stiffness by adding more carbon fiber plies. The former focuses on stiffness through geometry, while the latter focuses on stiffness through material.

The advantage of achieving stiffness through geometry lies in its efficient use of material, given that only four plies are used to form both links and joints. The mirrored double-pleat fold creates out-of-plane stiffening geometry and occupies a relatively small space. However, the large number of folds required by the mirrored double-pleat make it difficult to construct joints void of defects. The accummulation of defects from many mirrored double-pleat patterns leads to bulk imprecisions in the resulting linkage. Defects of the linkage included undesired deformations, protruding strands, and undesired diffusion of silicone.

On the other hand, by adding more plies, stiffness is achieved by curing more rigid carbon fiber sheets. With this process, the number of folds and space occupied was minimal. However, this came at the cost of nearly doubling the usage of carbon fiber sheet, and involved many smaller cutouts during layup. Nonetheless, this method was selected to produce a model of an active aerodynamic spoiler. The purpose of this prototype was to demonstrate the usage of this fabrication technique, but also to highlight a class of applications that would benefit from this sort of construction. In particular, both automobile and aerospace structures serve to benefit from lightweight, stiff structures that could sit flush to a surface, then fold out.

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